



Prompt and Delayed Fission Neutrons in Active Interrogation by Monoenergetic and Multimodal Radiation Sources

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Many applications require detection of fissionable material



Cargo scanning



Treaty verification/arms control

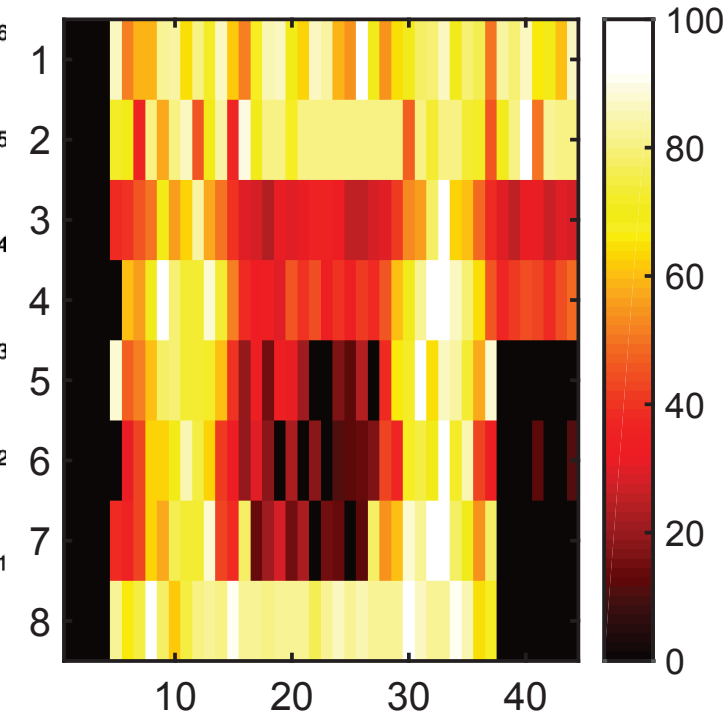
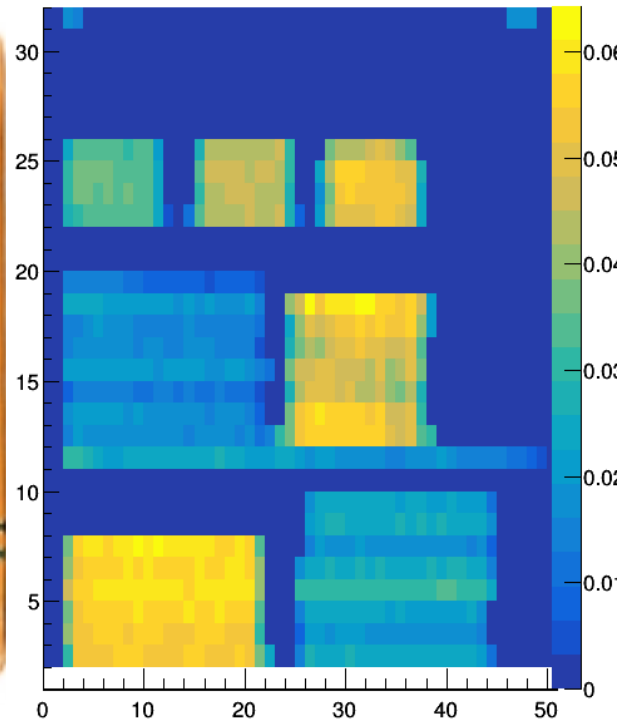
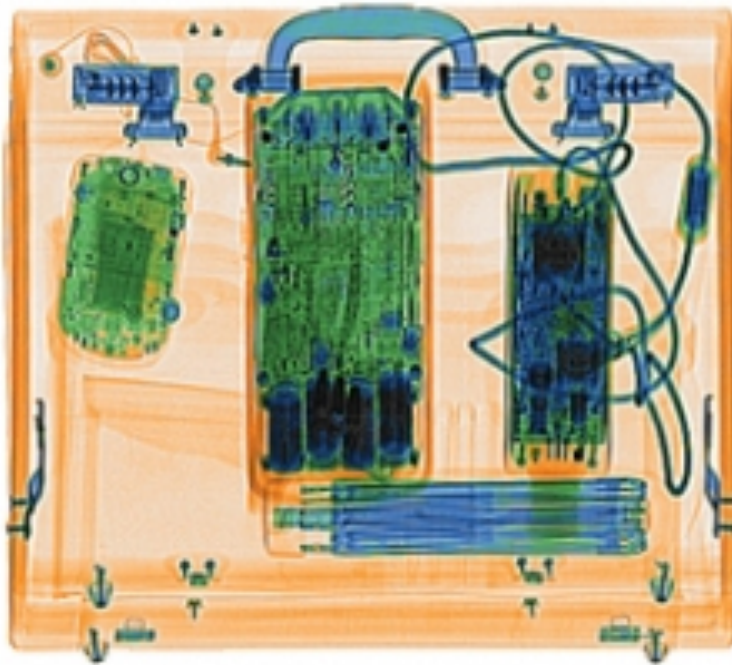


Wide area search



Safeguards

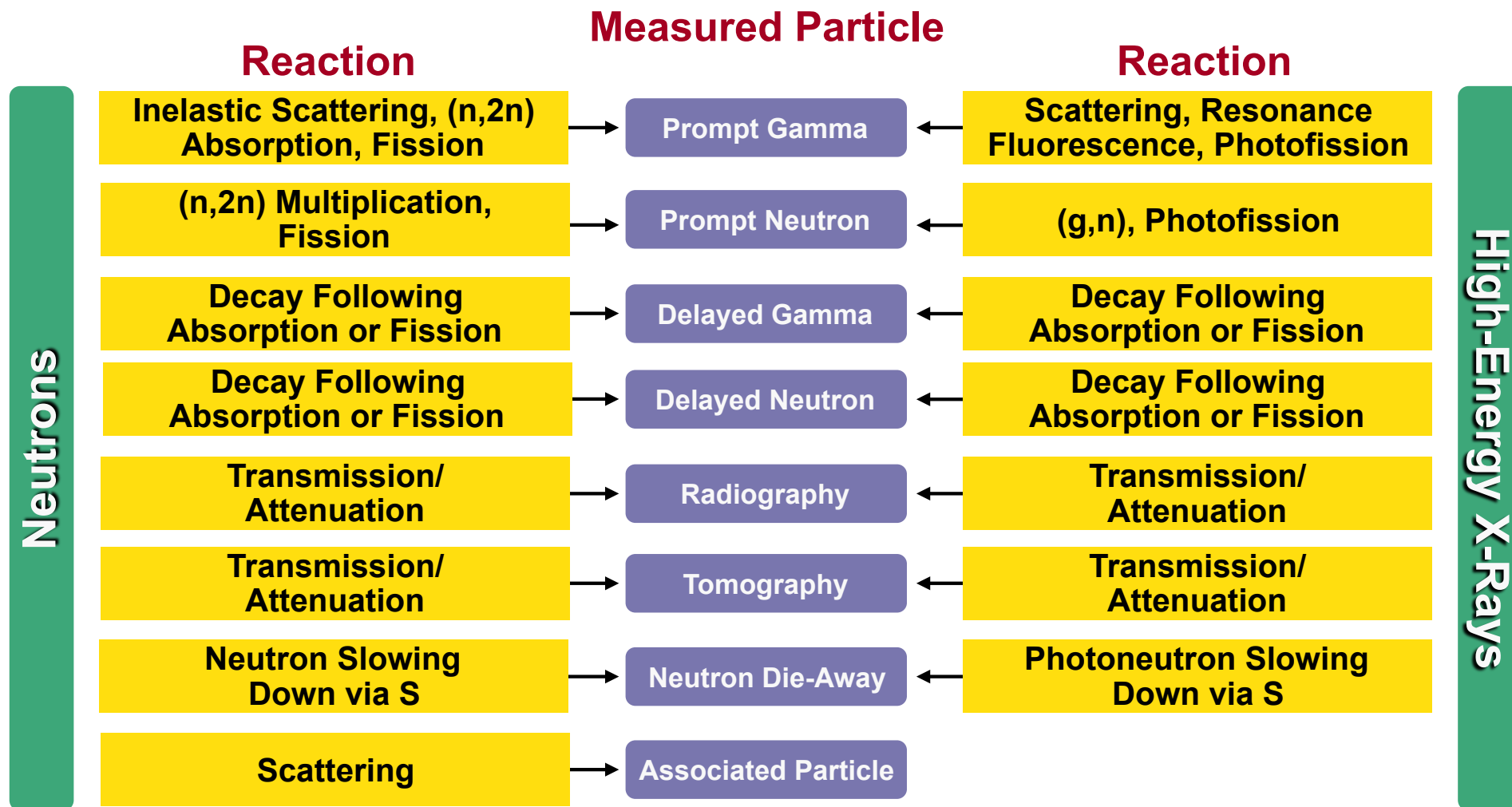
Radiographic methods are powerful, but...



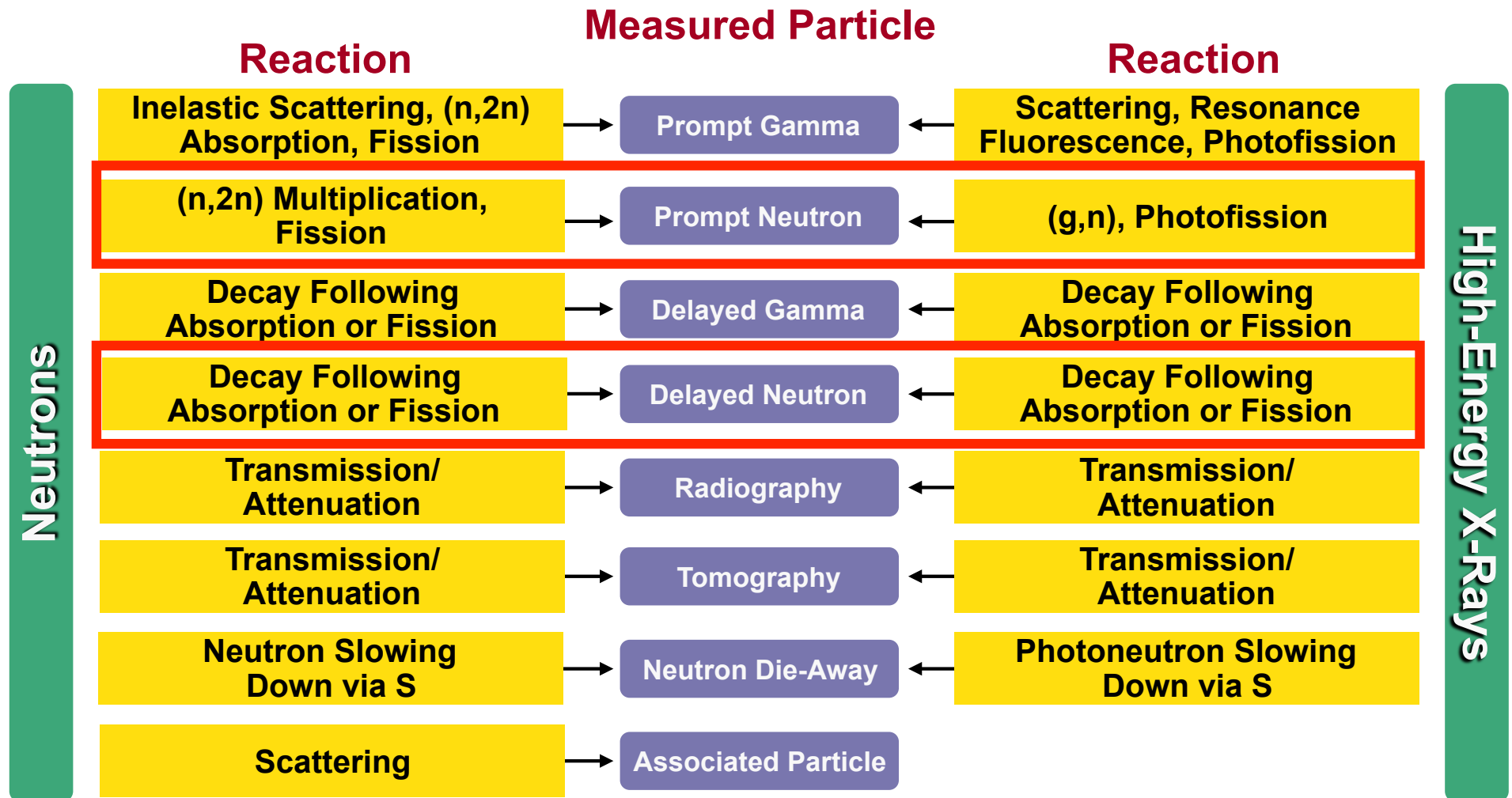
Typically there is no isotopic selectivity and contrast may not be sufficient to uniquely identify different elements.

Exceptions: NRF, neutron resonance radiography

We desire to detect unique signatures of fissionable materials



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We experimentally investigated prompt and delayed neutron measurements in different AI environments

Major goals:

- Study practical aspects of measurements in AI (probes, detectors, DAQ)
- Determine the extent to which simulations can predict the details of experimental outcomes (such as yields and emission time profiles)

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Treaty verification scenario:

DD interrogation
prompt neutrons



portable neutron generator

Cargo scanning scenario:

$^{11}\text{B}(d,n)^{12}\text{C}$ interrogation
delayed neutrons



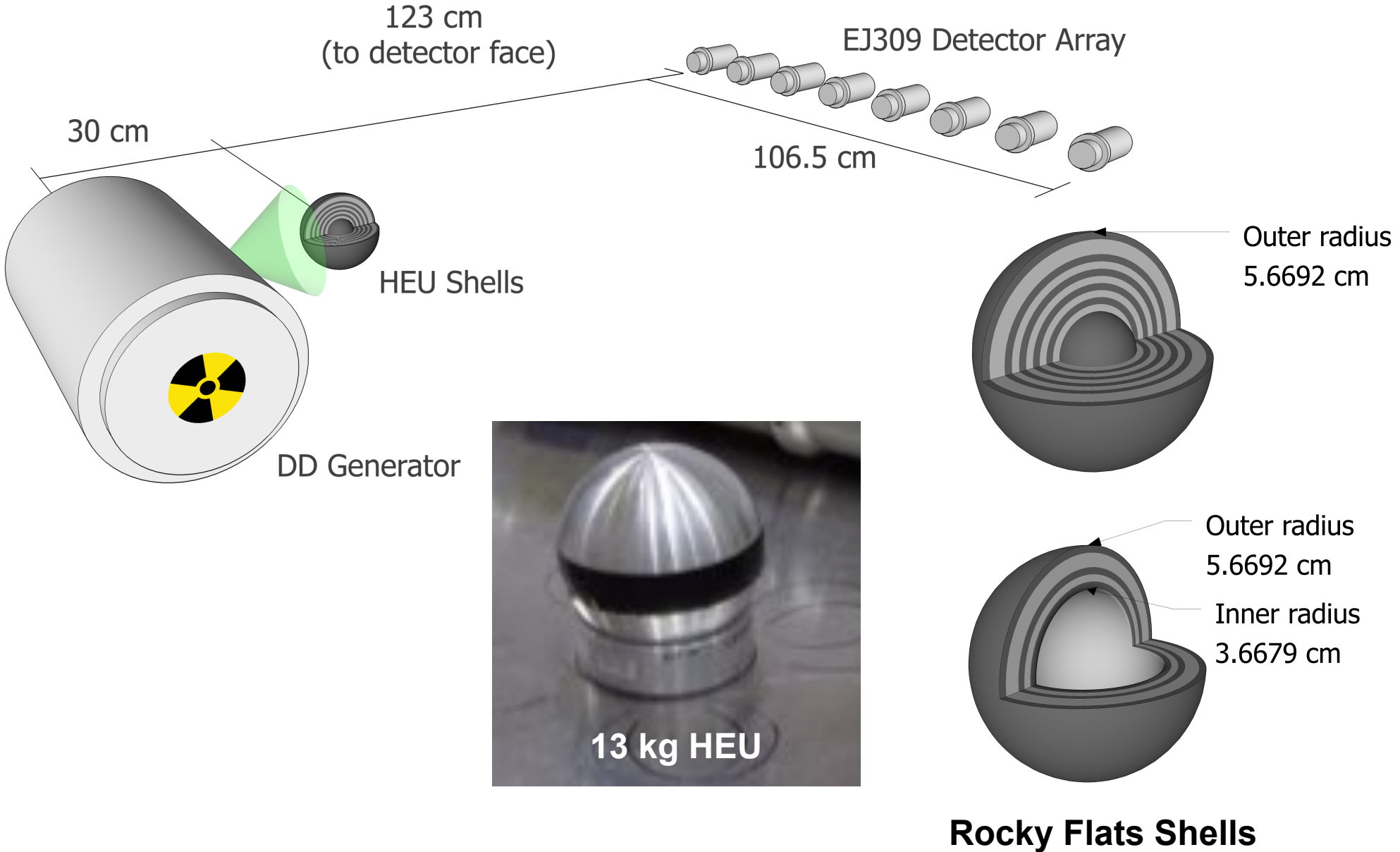
RFQ accelerator

We conducted measurements at the Nevada National Security Site

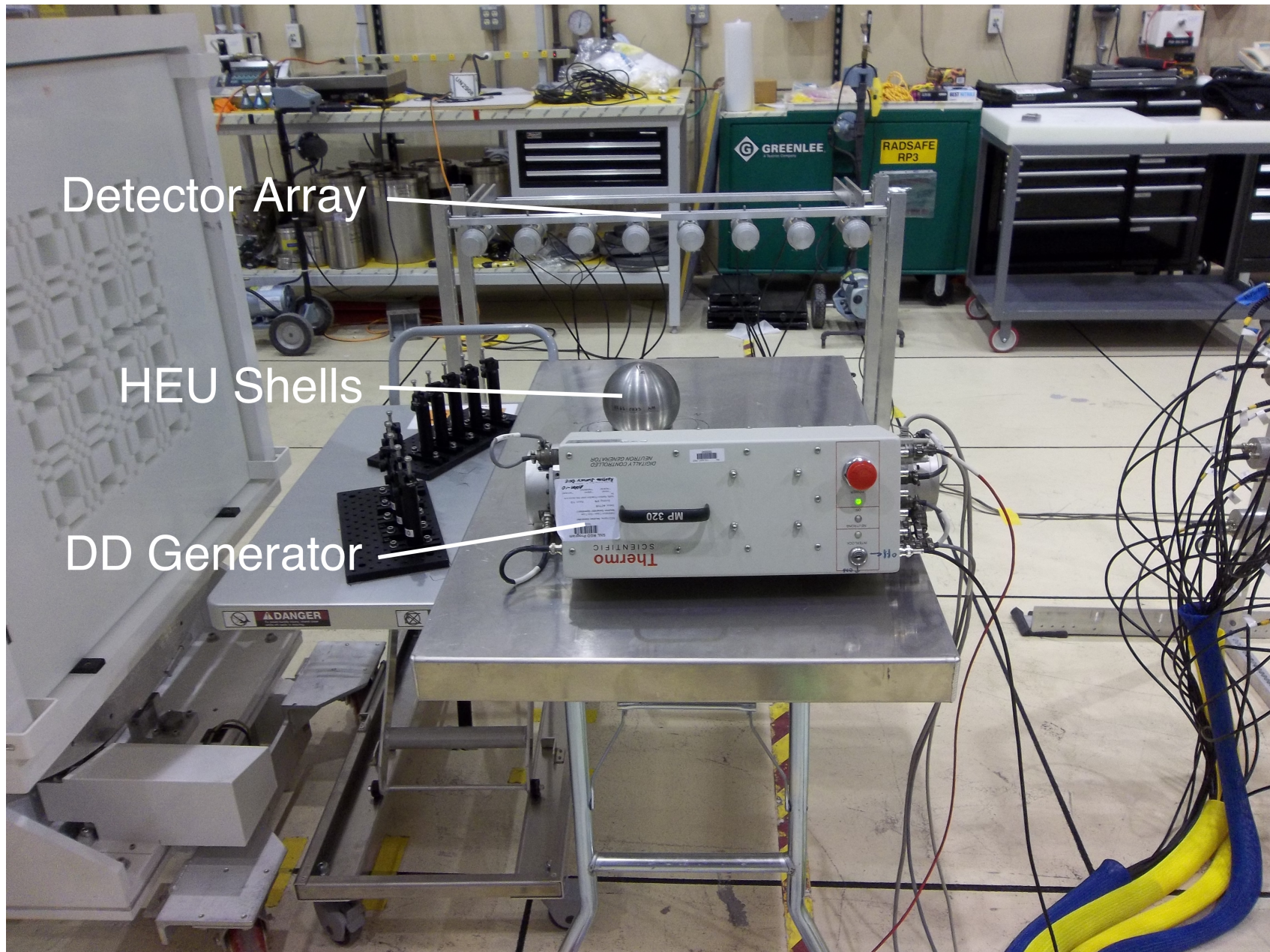


Device Assembly Facility

A flexible shell-like configuration of HEU was used with a primary goal to conduct transmission neutron imaging



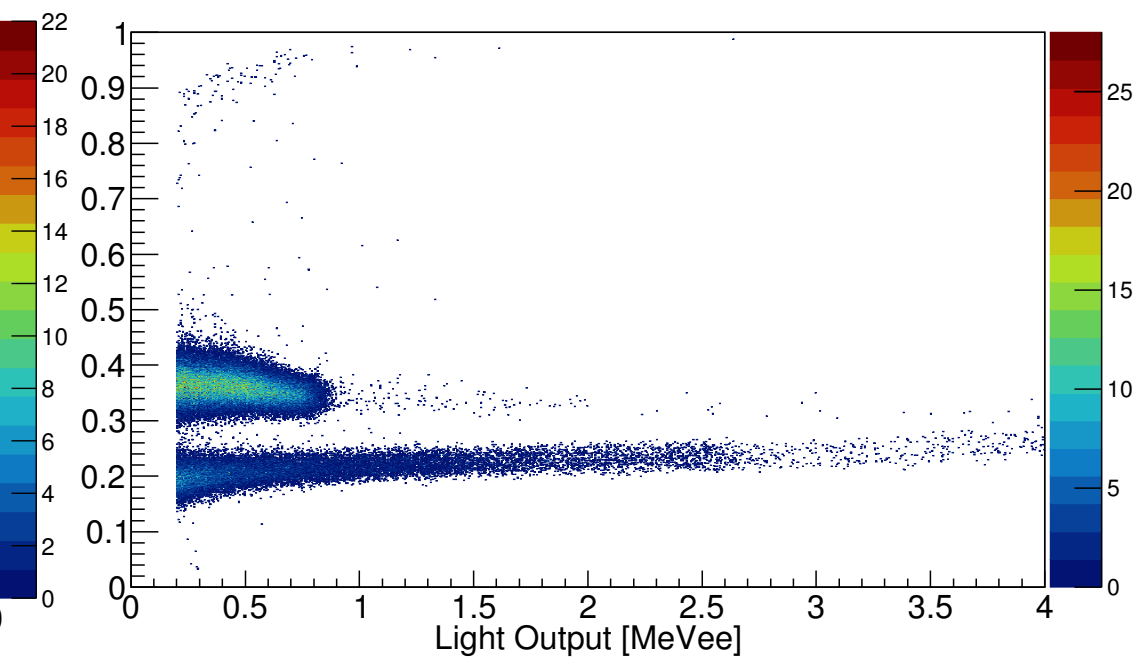
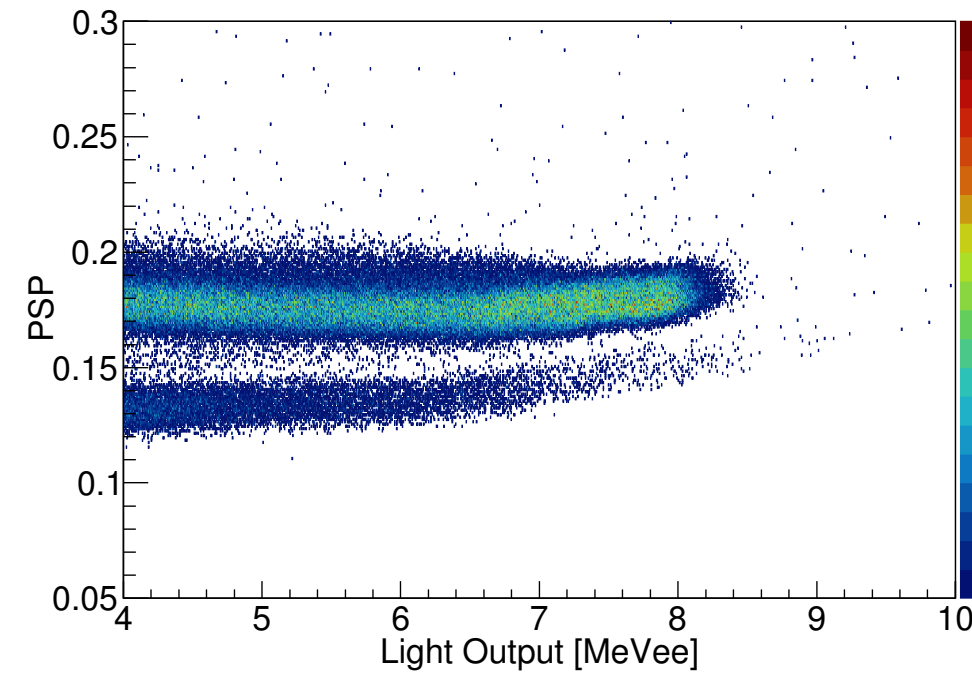
A transmission geometry was implemented with DD and DT neutron sources and a linear array of liquid scintillators



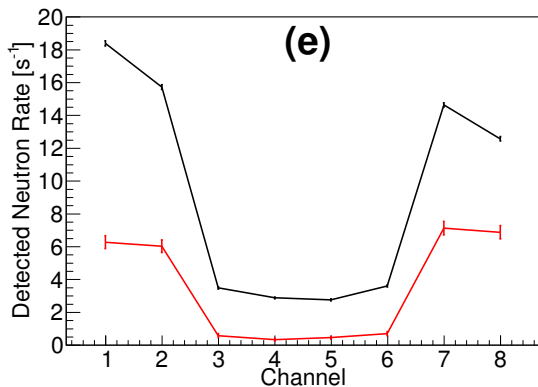
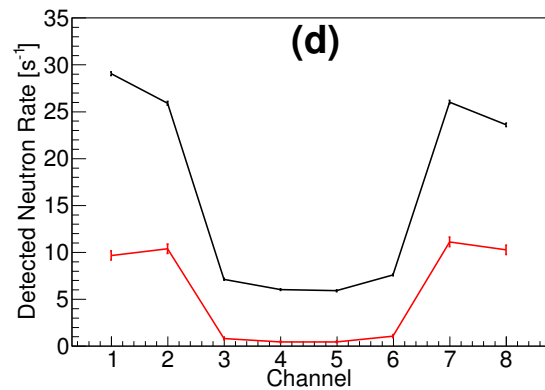
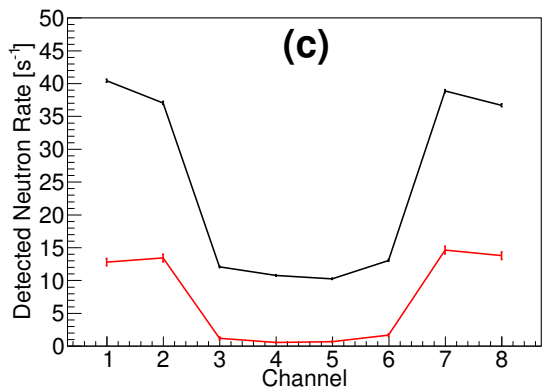
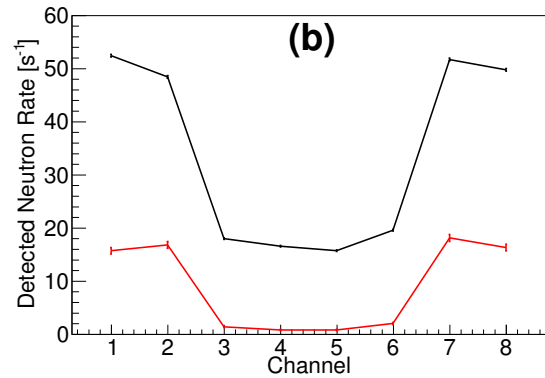
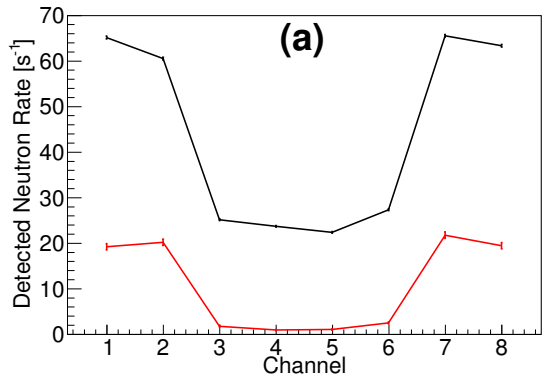
We used both DD and DT neutrons

DT

DD



A common practical issue when trying to reconcile simulations and experiments is the room return



Experiment
Simulation (Geant4)

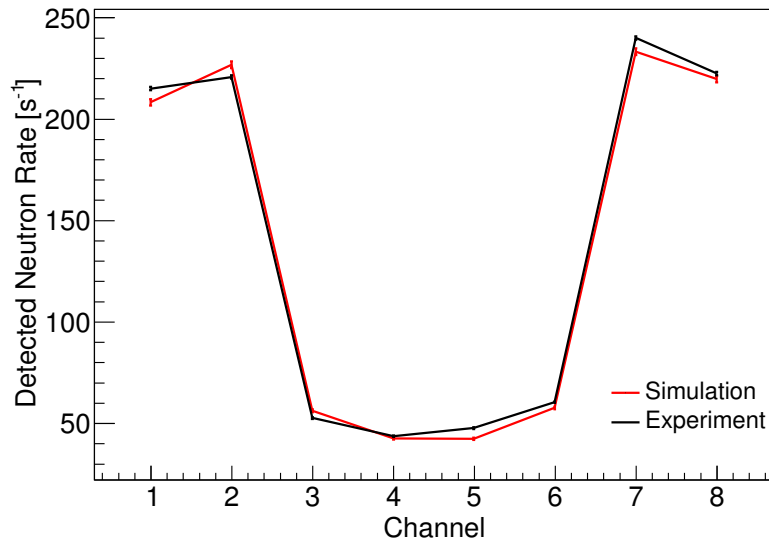


**Increasing
threshold
on detector
light output**

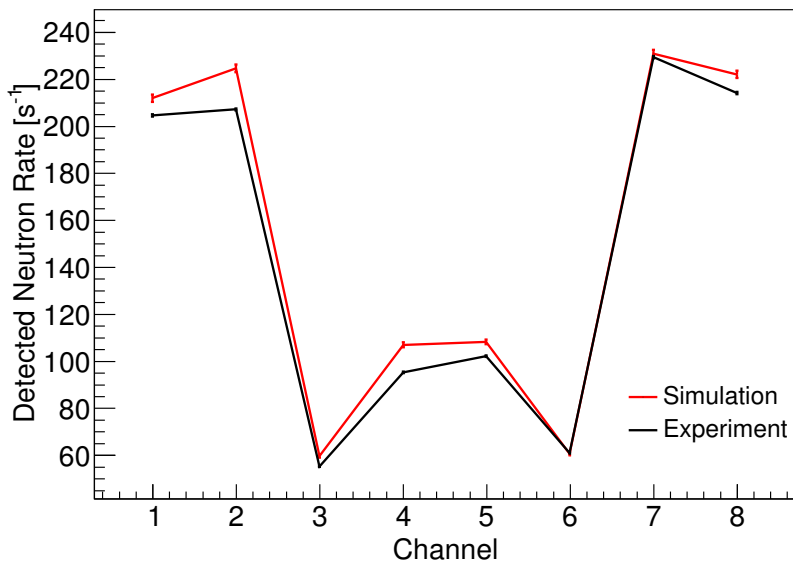
A constant scaling factor was still needed to achieve good agreement between simulation and experiment.

Sensitivity to object geometry (diversion resulting in geometric anomaly) was demonstrated

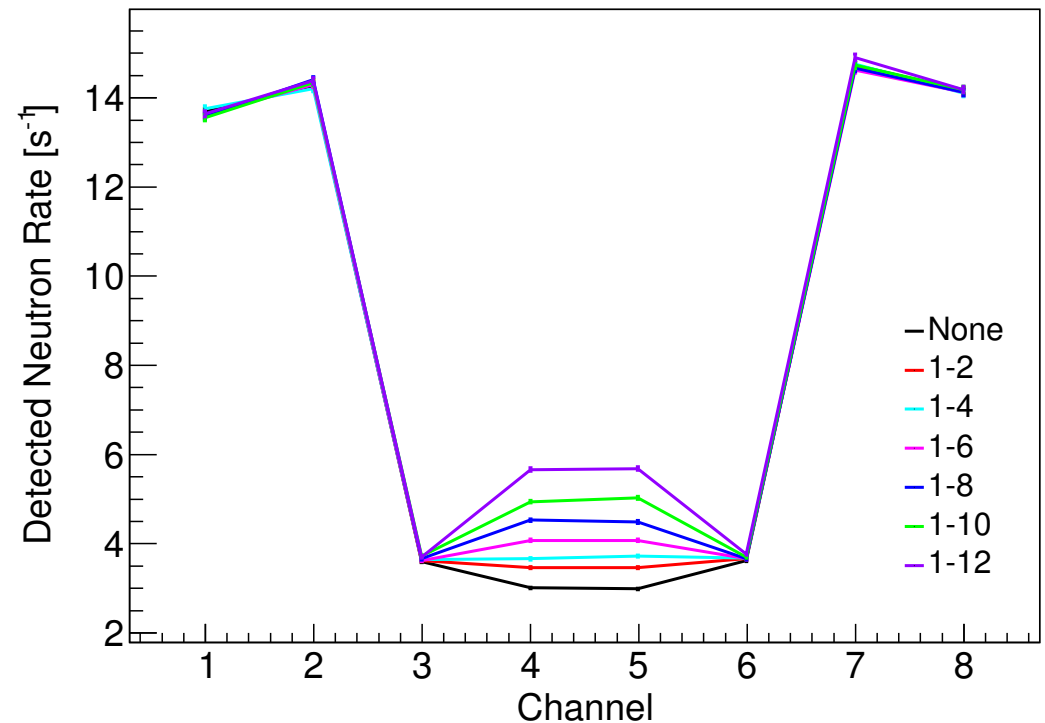
“Full” configuration



“Half” configuration

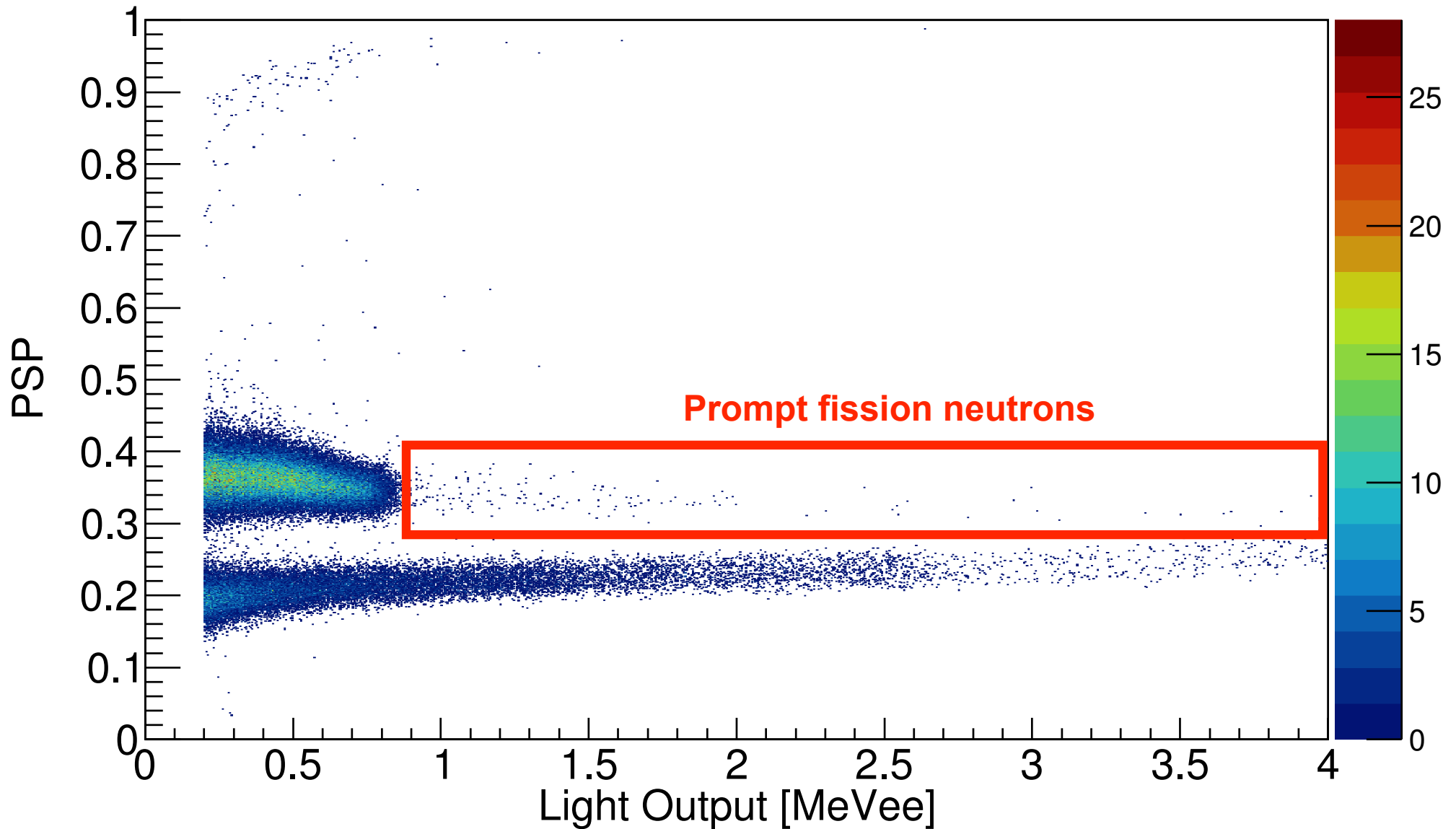


Simulation of shell removal

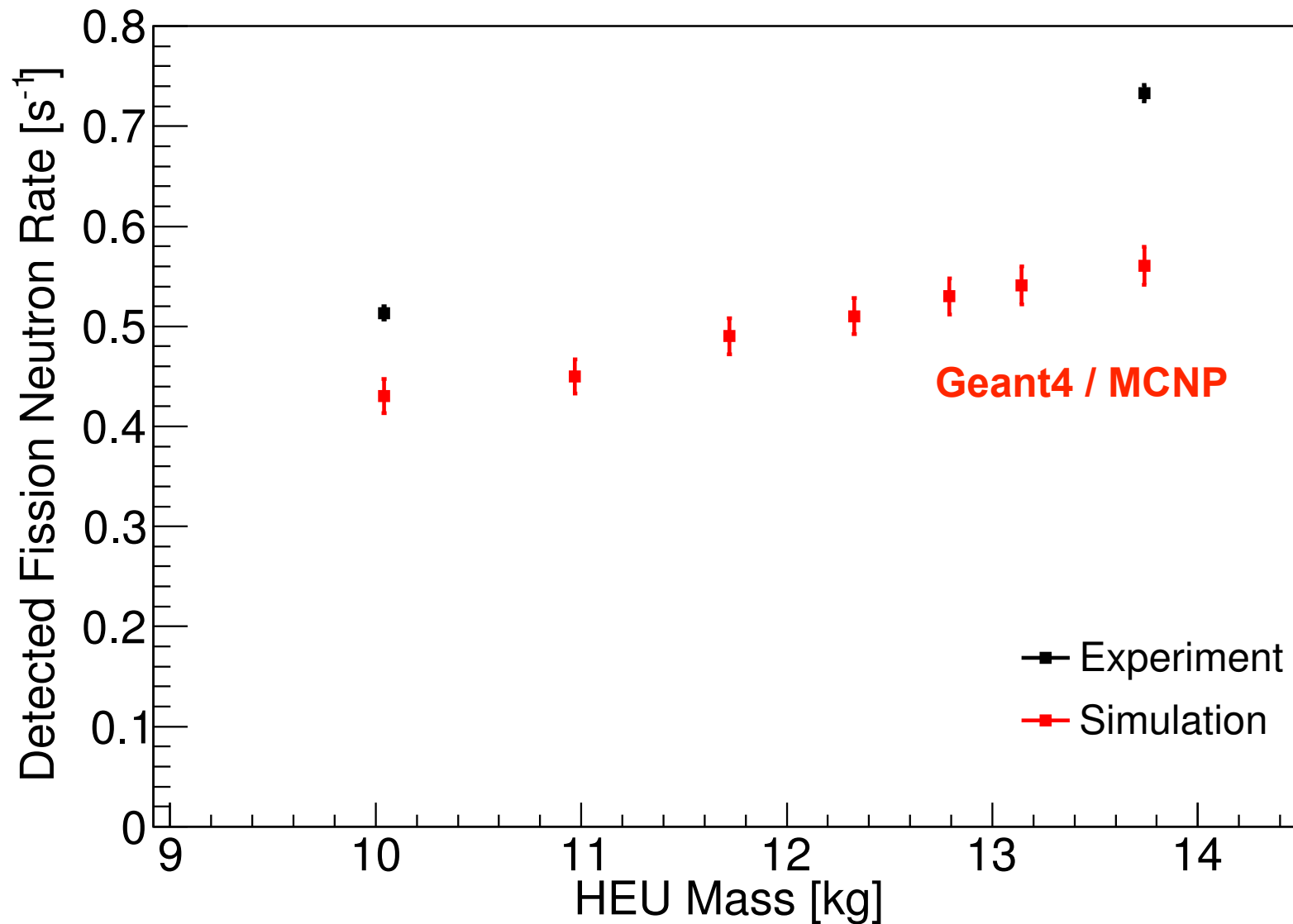


This agreement between experiment and simulation was used to determine the angular neutron flux produced by the neutron generator.

We imposed a higher light output threshold to measure the prompt fission neutron rate



We simulated the detected prompt fission rate and compared it with experiment



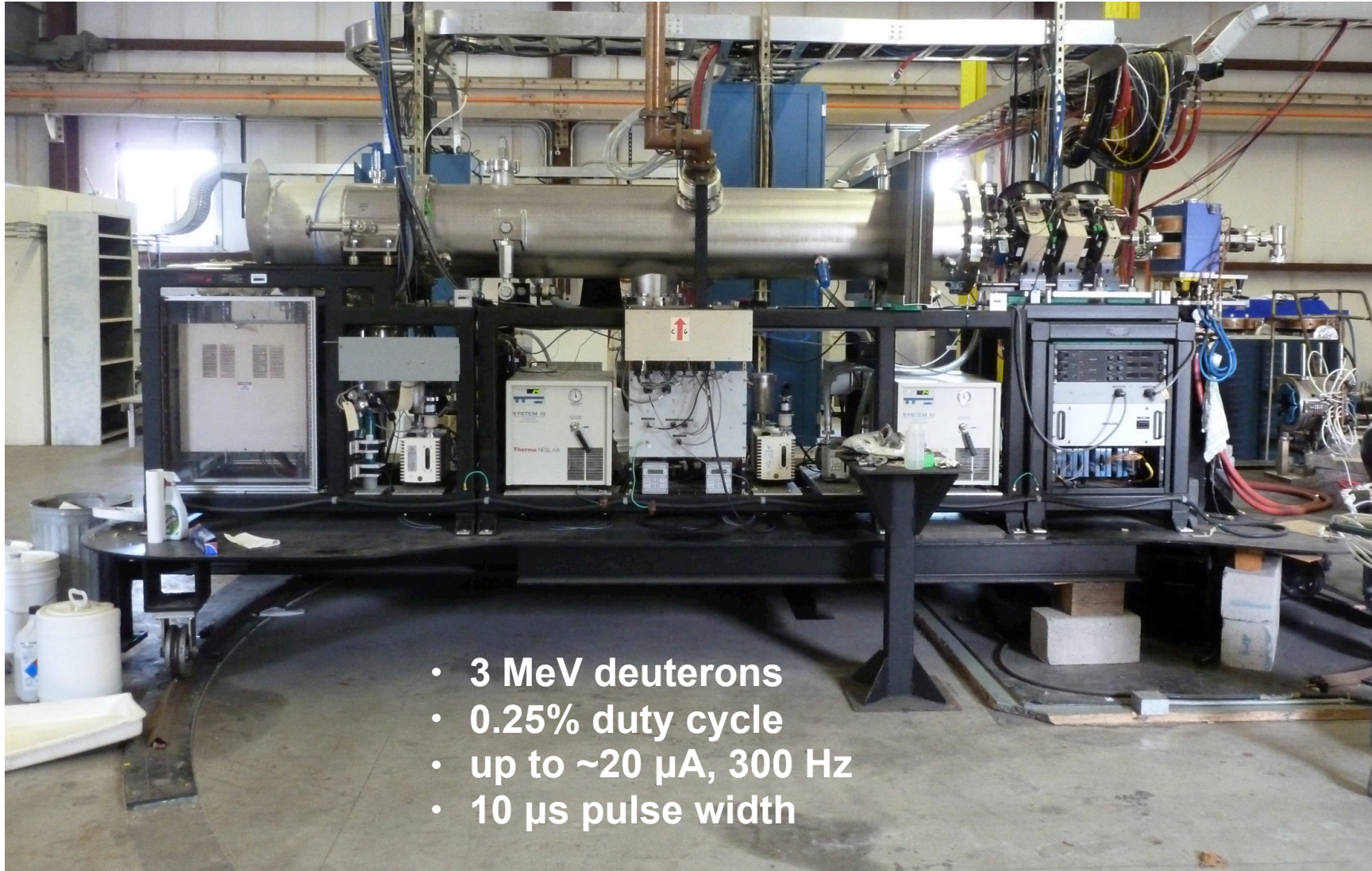
We have been using the MIT Bates RFQ for proof-of-principle cargo scanning experiments



Georgia Institute
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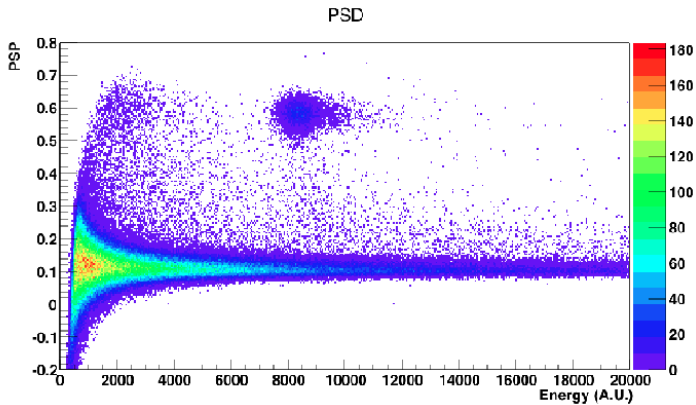
PennState



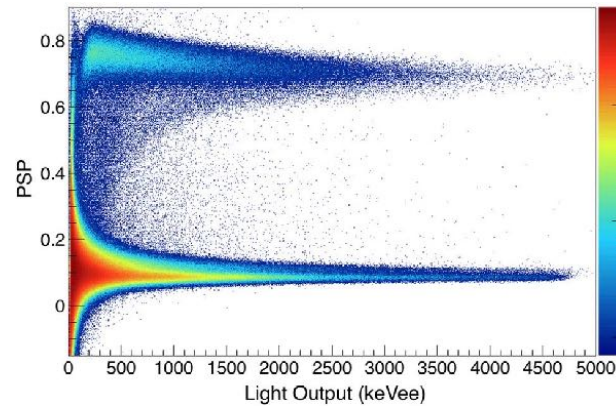
- 3 MeV deuterons
- 0.25% duty cycle
- up to $\sim 20 \mu\text{A}$, 300 Hz
- 10 μs pulse width

We developed specialized detectors suitable for measuring the delayed neutron signal

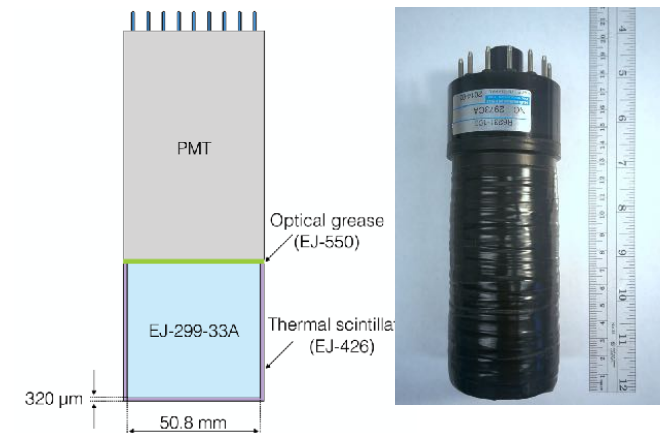
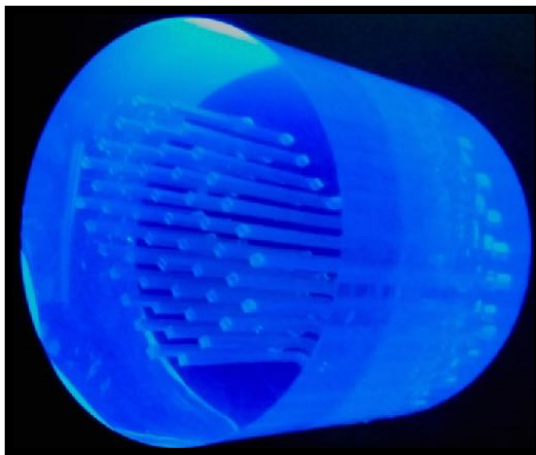
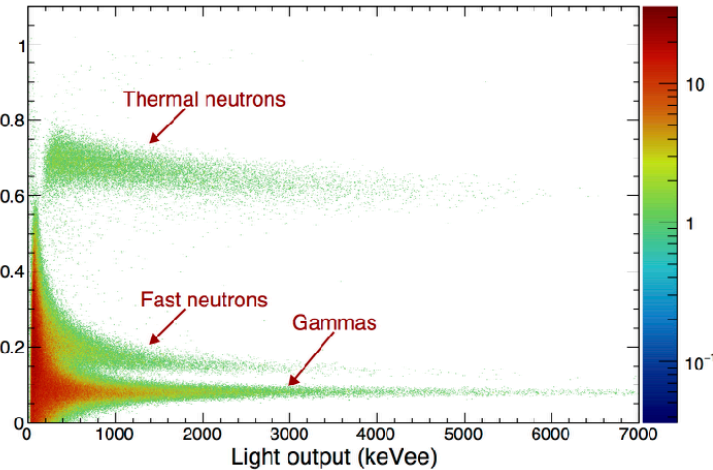
PVT-⁶Li glass composites



PVT-⁶LiF:ZnS(Ag) composites



“Triple PSD” composites



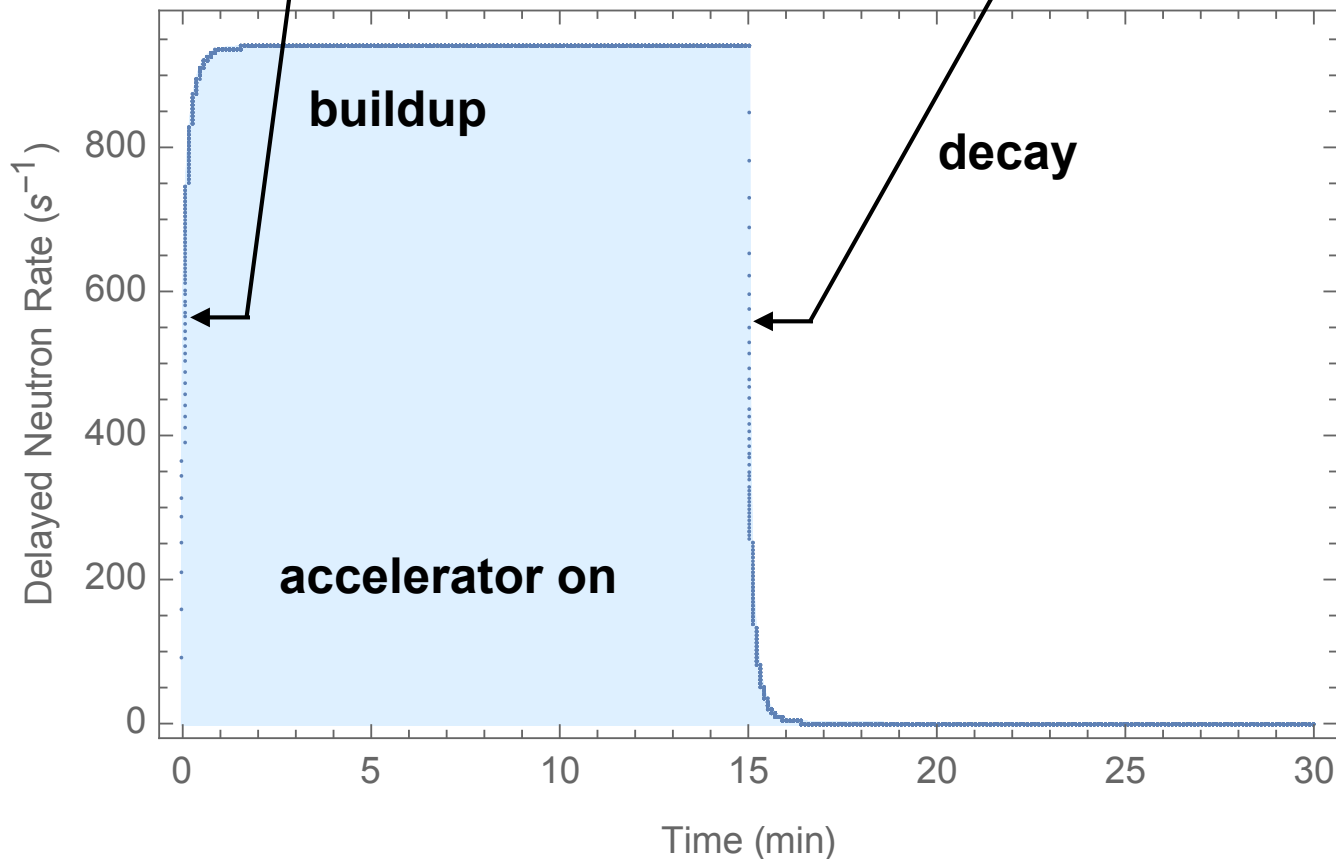
M. Mayer et al., NIMA 785, 117-122 (2015)

K. Wilhelm et al., NIMA 842, 54-61 (2017)

M. Sharma et al., NIMA 857, 75-81 (2017)

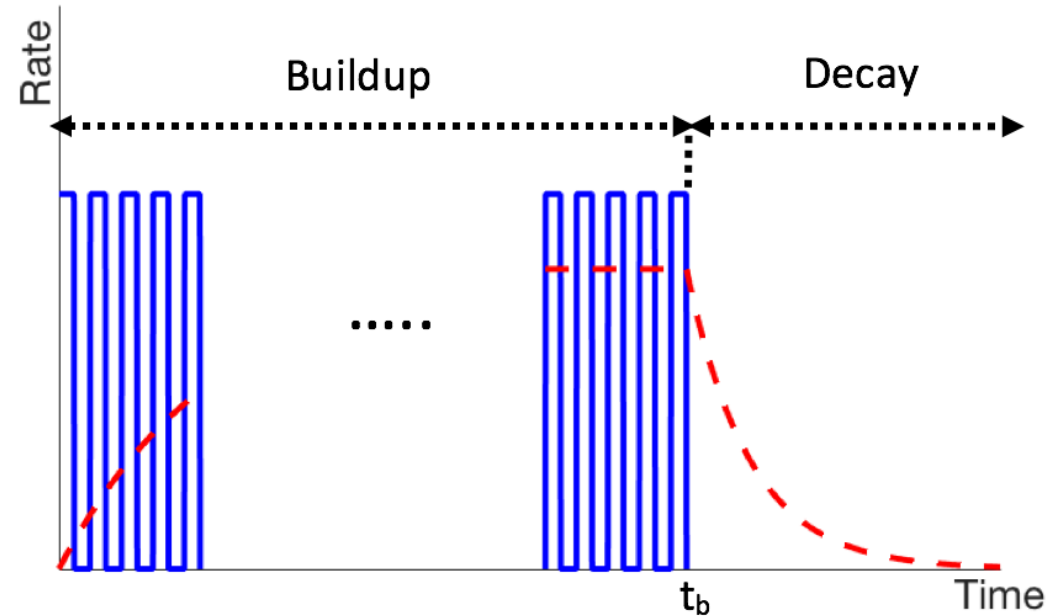
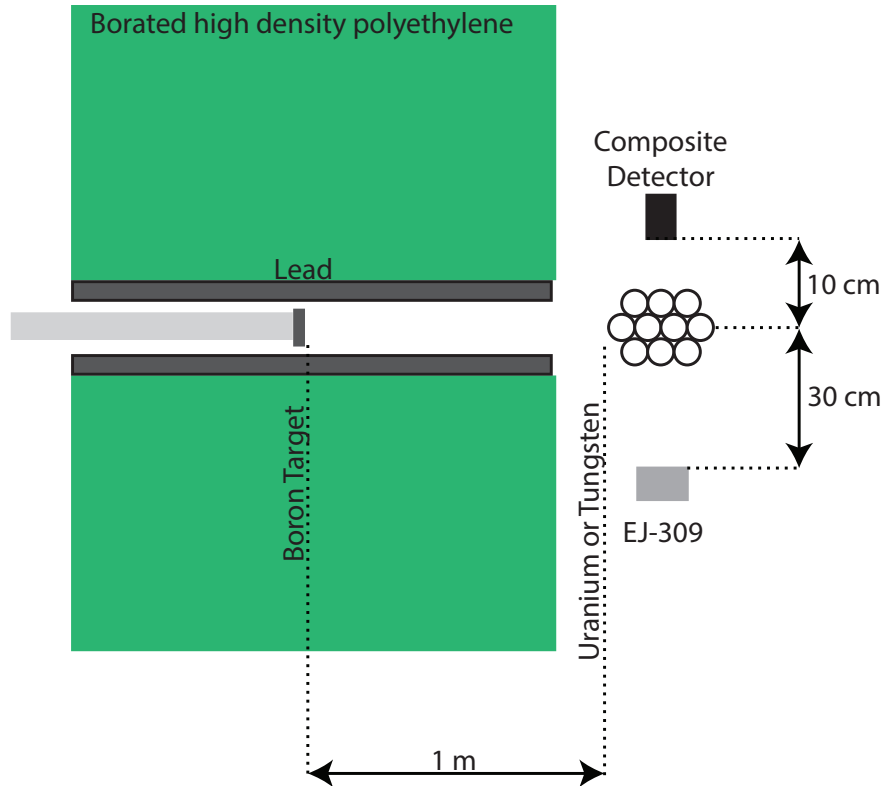
Neutrons from long-lived delayed neutron groups can be used to infer the occurrence of fission

$$R_b(t) = B + C \sum_{i=1}^6 Y_i \epsilon_i (1 - \exp(-t/\tau_i))$$
$$R_d(t) = B + C \sum_{i=1}^6 \epsilon_i Y_i (\exp(t_b/\tau_i) - 1) \exp(-t/\tau_i)$$

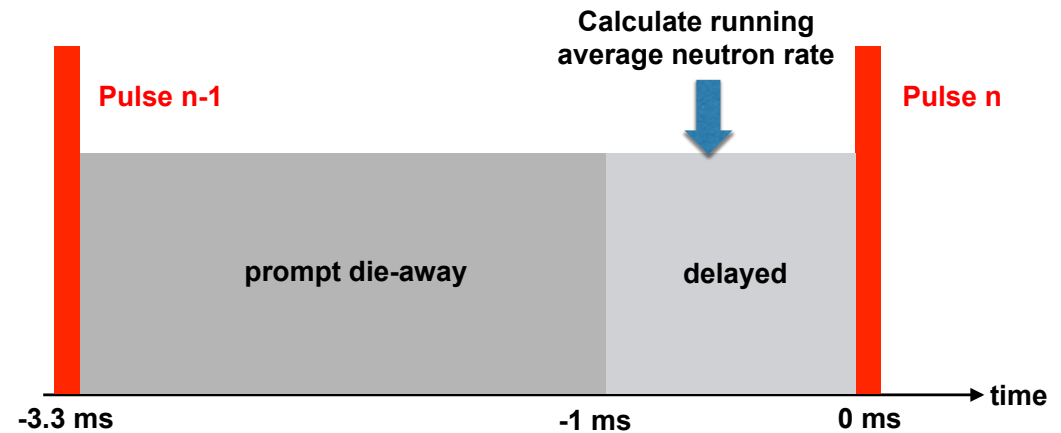


<1% of neutron are delayed; emitted over scale of up to 10's of seconds.

We conducted delayed neutron measurements using the $^{11}\text{B}(\text{d},\text{n})^{12}\text{C}^*$ active interrogation source

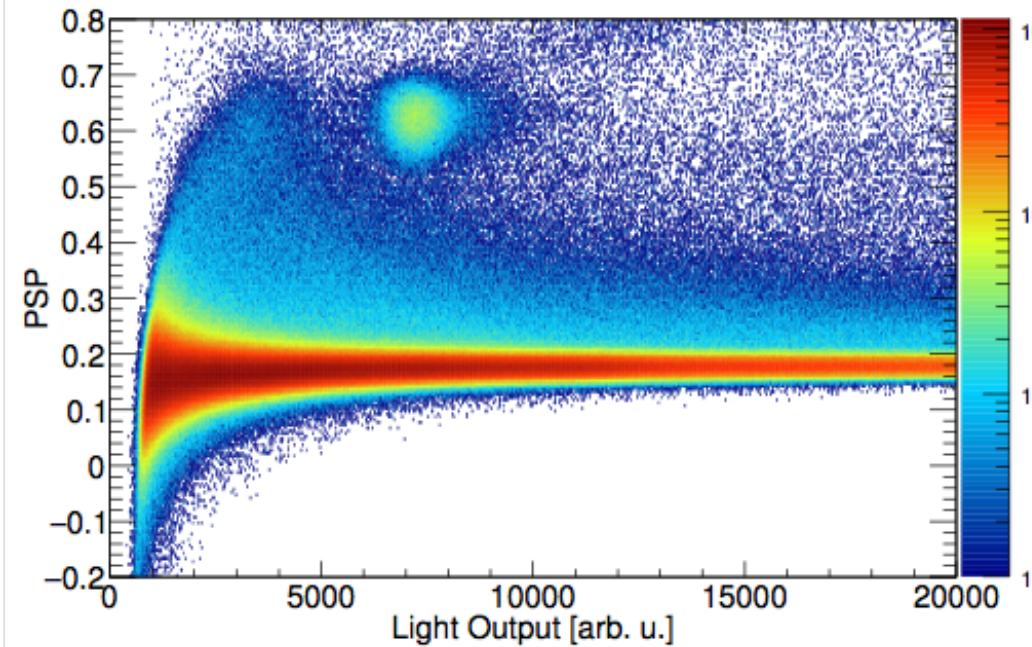


4.4 MeV: $5.3 \times 10^7 \text{ s}^{-1} \mu\text{A}^{-1}$
15.1 MeV: $6.2 \times 10^6 \text{ s}^{-1} \mu\text{A}^{-1}$
Fast neutrons: $1.3 \times 10^9 \text{ s}^{-1} \mu\text{A}^{-1}$

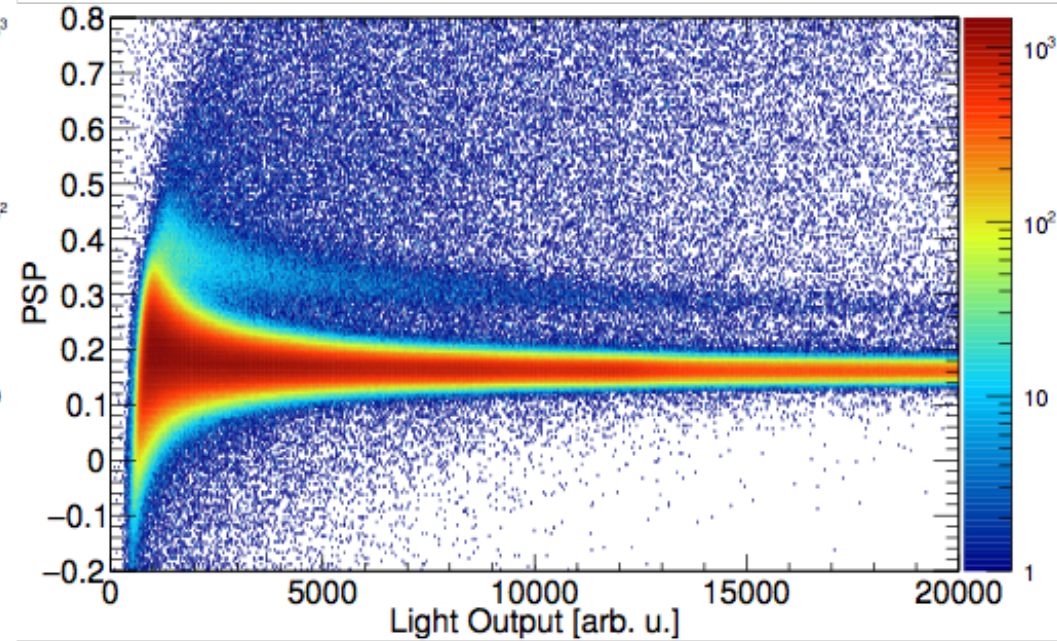


Typical PSD plots in AI environment

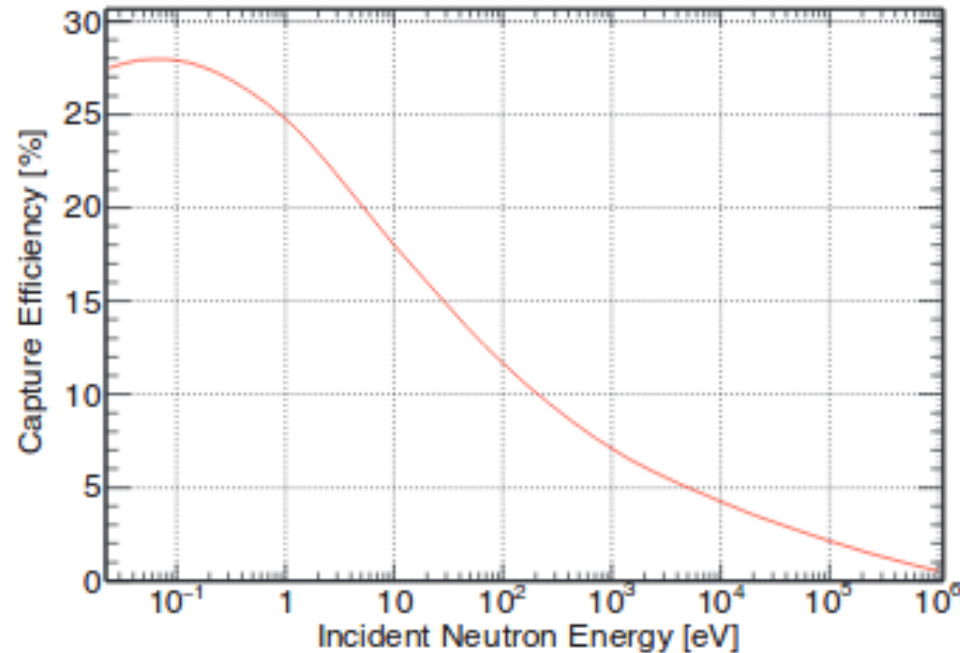
Composite capture-gated detector



Liquid scintillator (EJ-309)



We modeled the spectral evolution of delayed neutron emission and the energy-dependent detector efficiency



Capture gated detector exhibits a higher efficiency for low-energy neutrons.

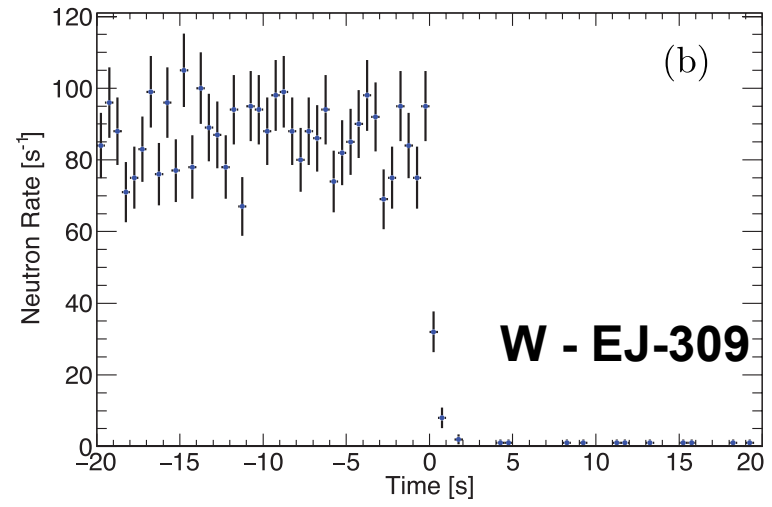
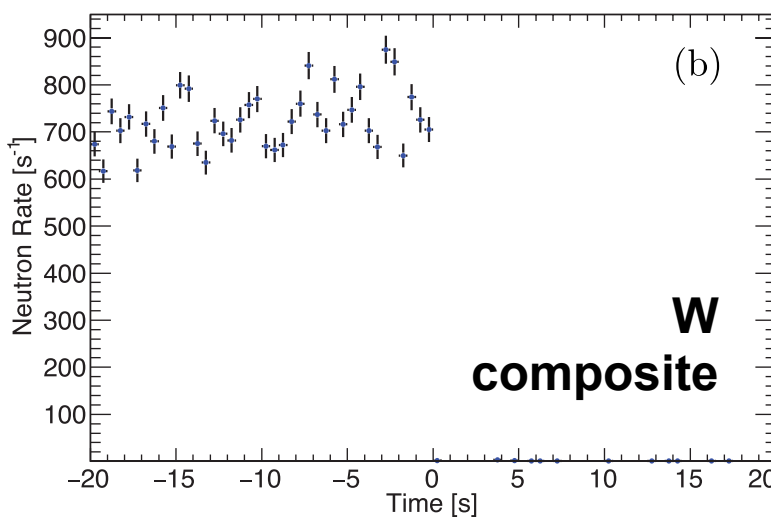
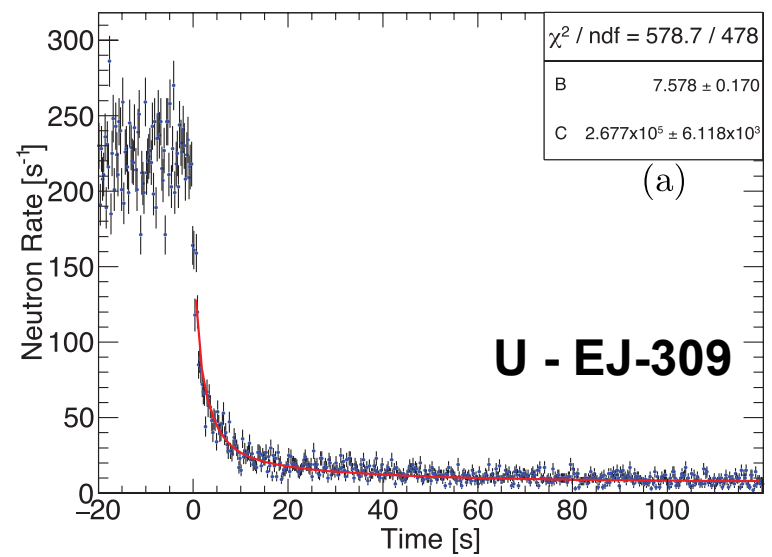
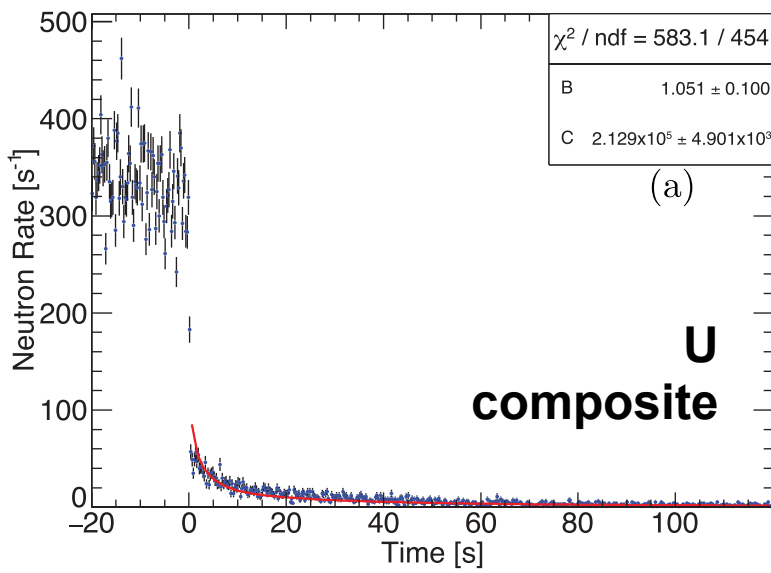
DN modeling parameters

Group	$Y(\%)$	ϵ_C	ϵ_R	$T_{1/2}$ (s)	τ (s)
1	0.054	0.01589	0.00028	52.38	75.56
2	0.564	0.01078	0.01115	21.58	31.13
3	0.667	0.01240	0.01136	5.00	7.21
4	1.599	0.01231	0.01744	1.93	2.78
5	0.927	0.01351	0.01220	0.490	0.71
6	0.309	0.01172	0.01501	0.172	0.25

Neutron background

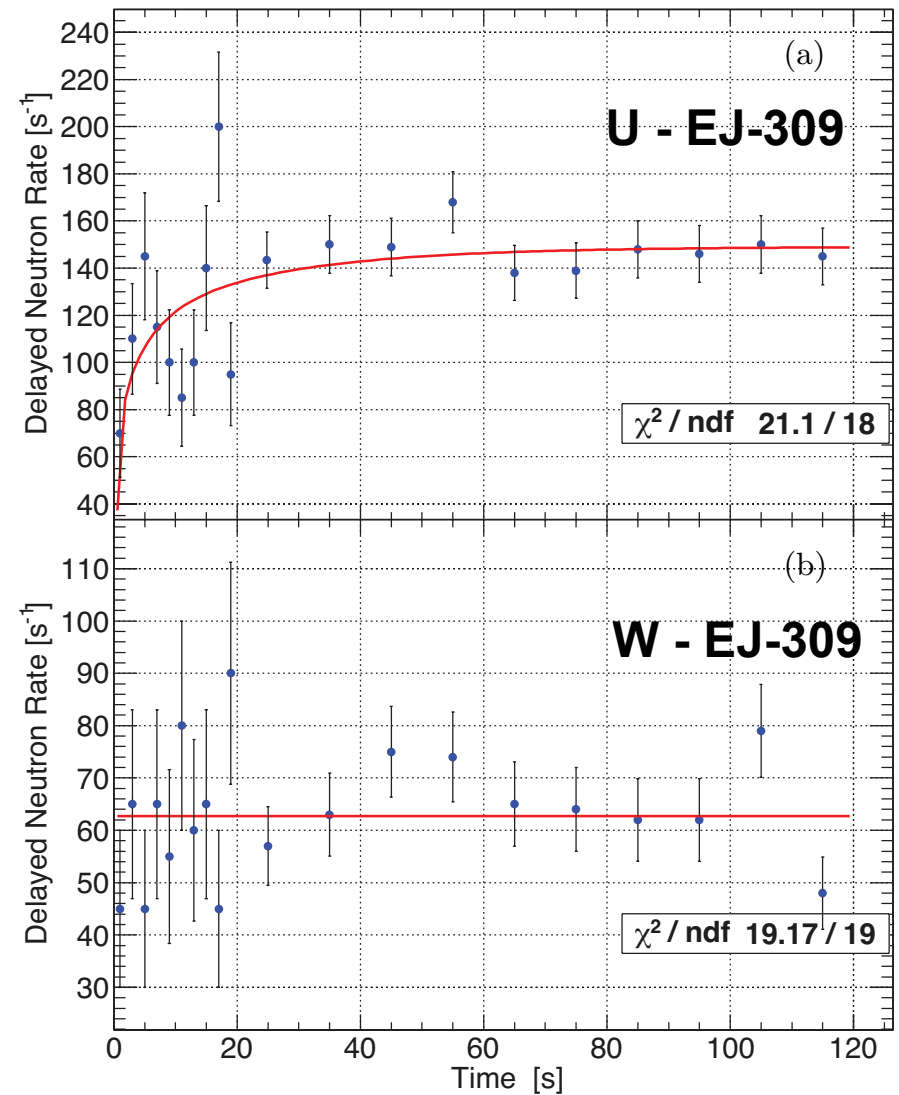
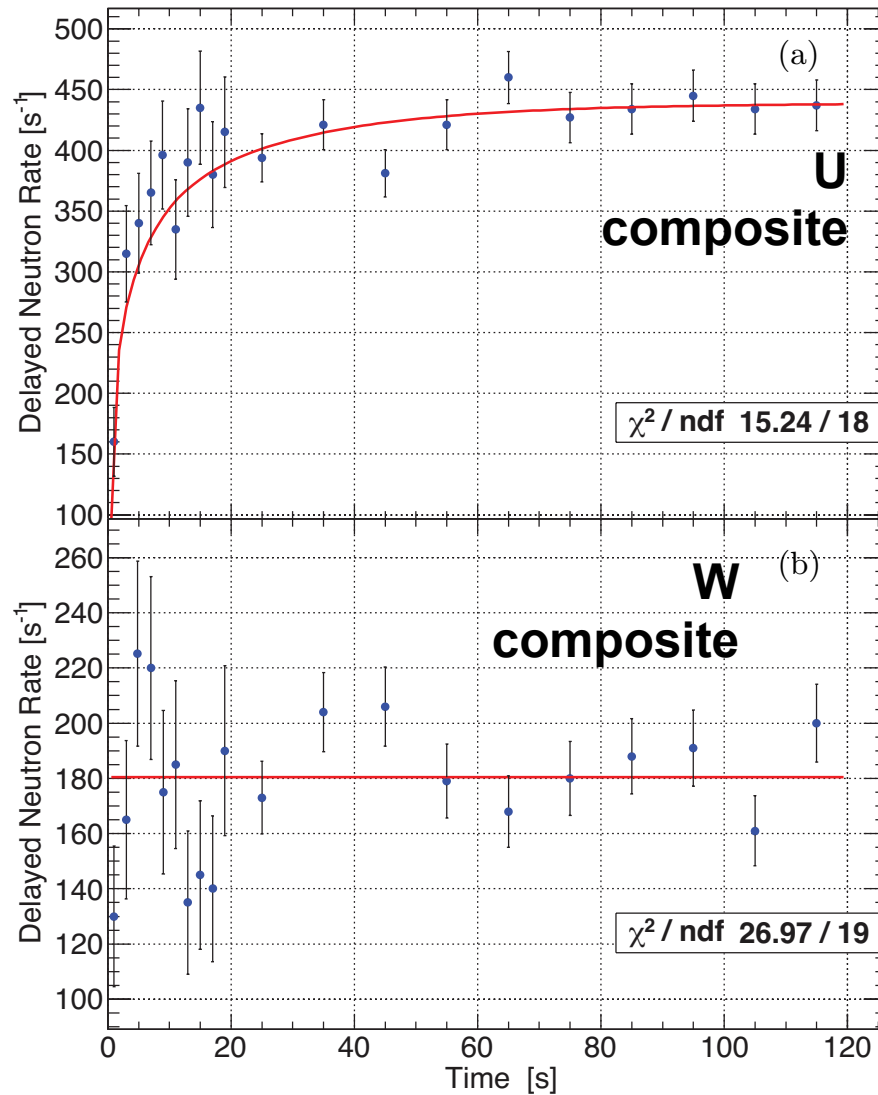
Source	Composite detector (s^{-1})	EJ-309 (s^{-1})
Cosmic rays	0.02	0.02
Spontaneous fission	0.03	0.2
^{17}N production	.0003–0.04	0.002–0.2

Delayed neutron emission **after** the accelerator beam is turned off



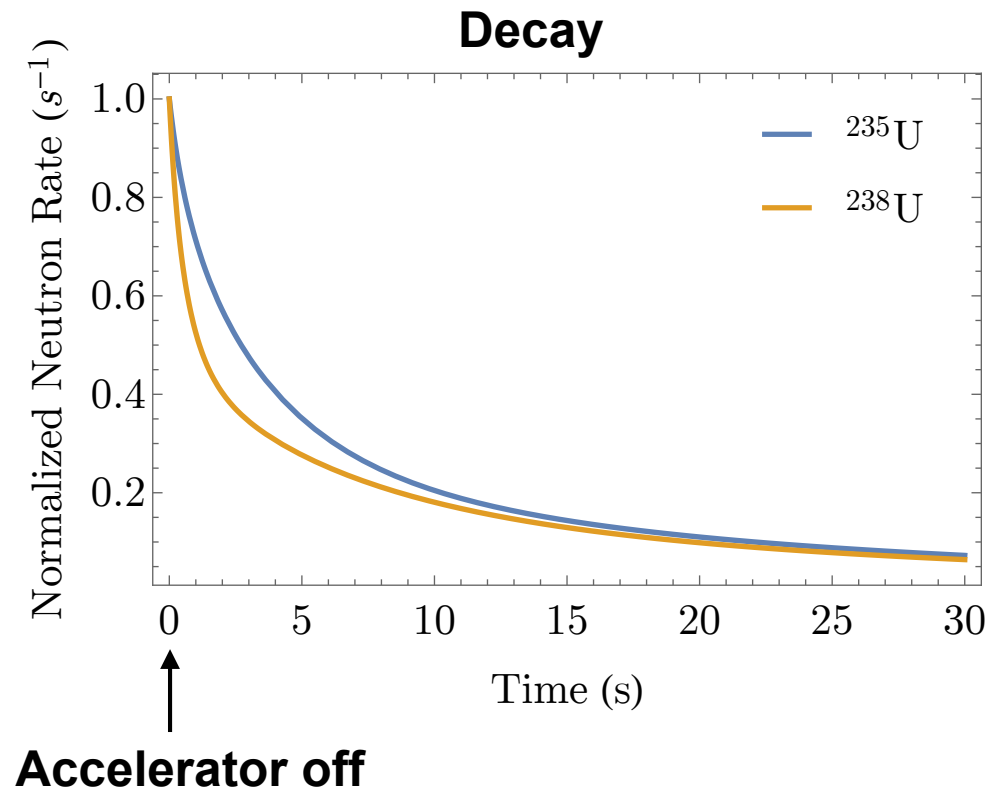
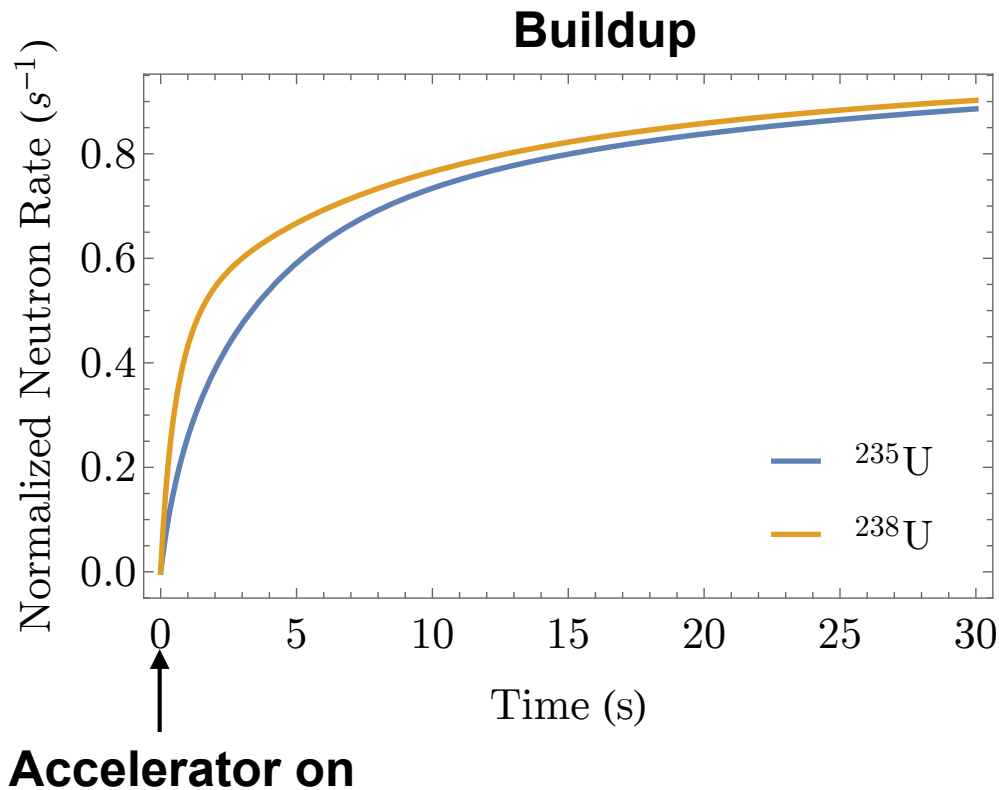
M. Mayer, J. Nattress, and I. Jovanovic, *Appl. Phys. Lett.* **108**, 264102 (2016).

Delayed neutron buildup measured **between** accelerator pulses

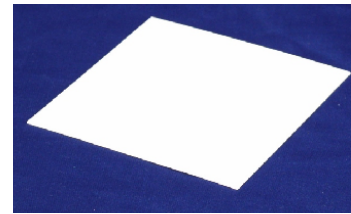
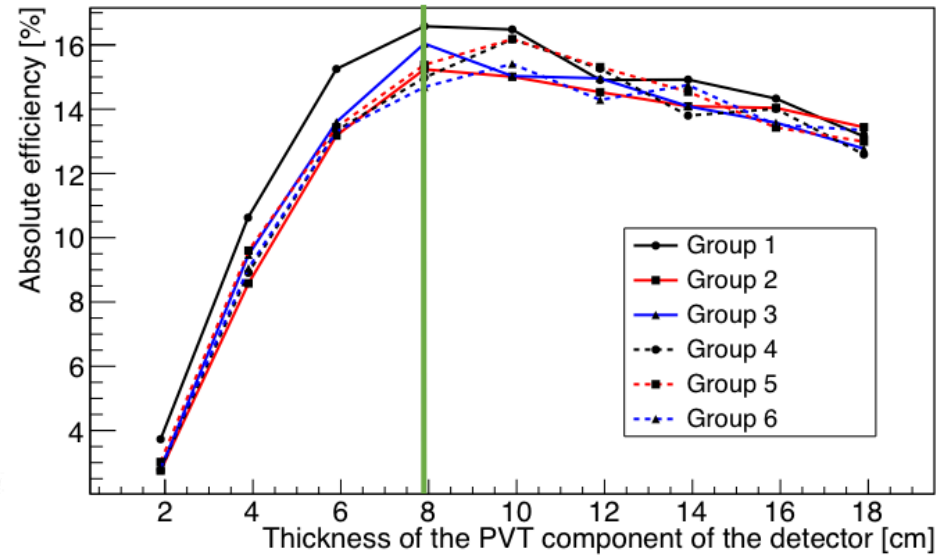
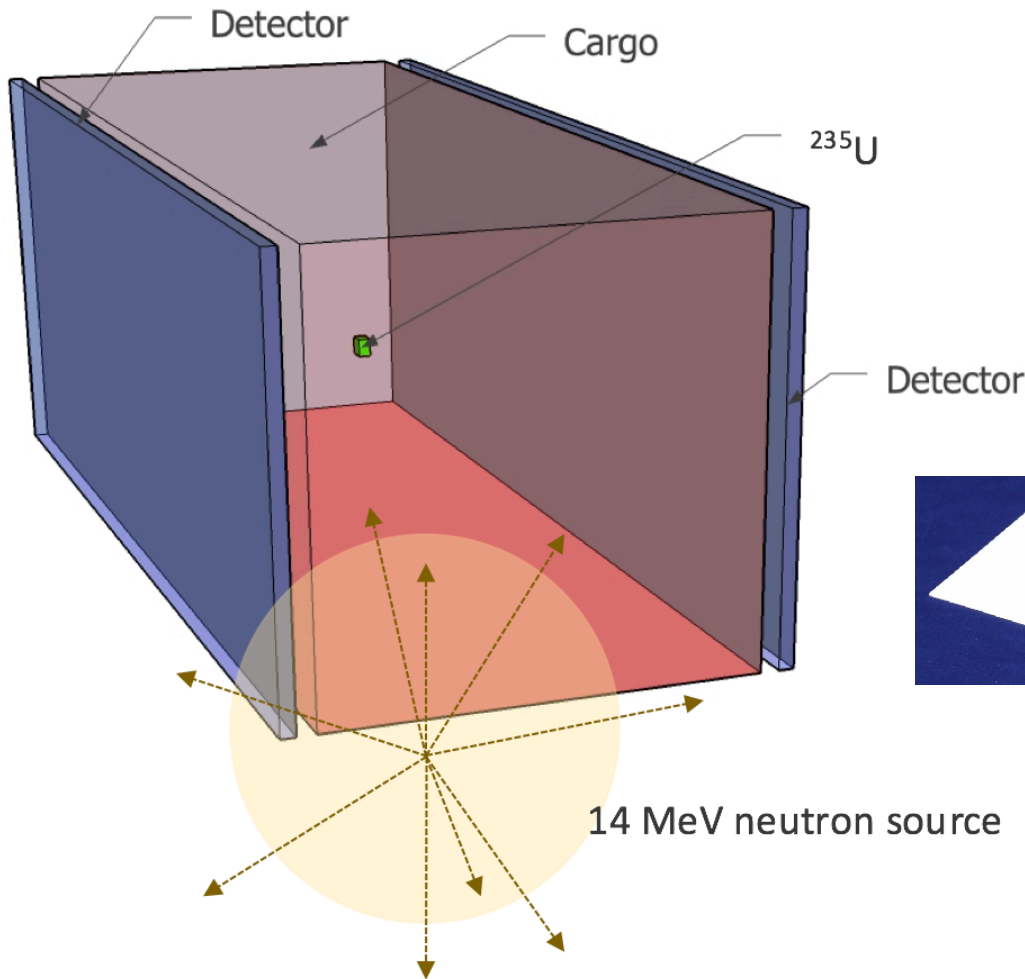


M. Mayer, J. Nattress, and I. Jovanovic, *Appl. Phys. Lett.* 108, 264102 (2016).

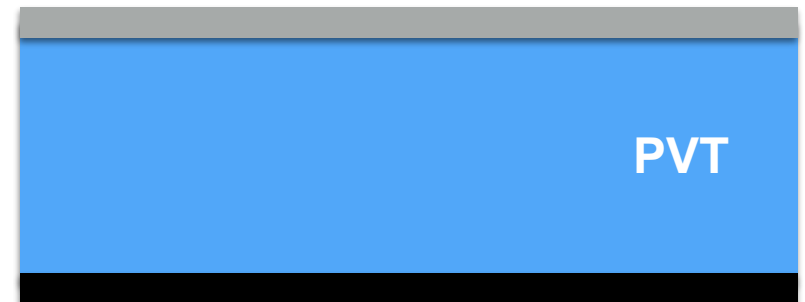
Discrimination of ^{238}U from ^{235}U based on the time profile of delayed neutron emission



Scaling delayed neutron measurements to large detector areas



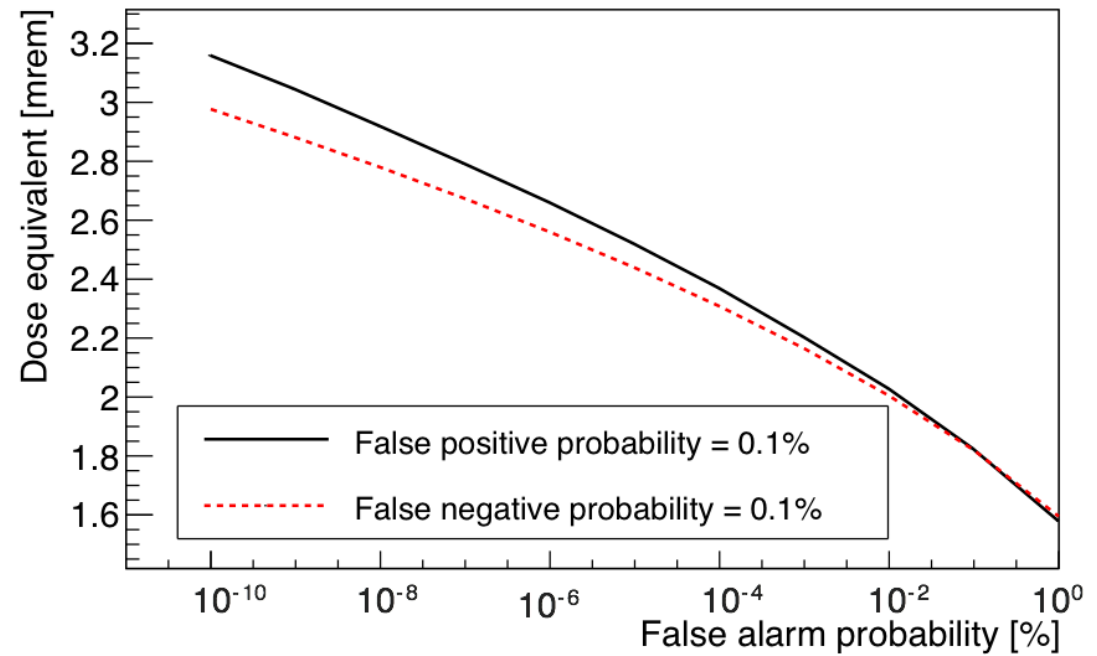
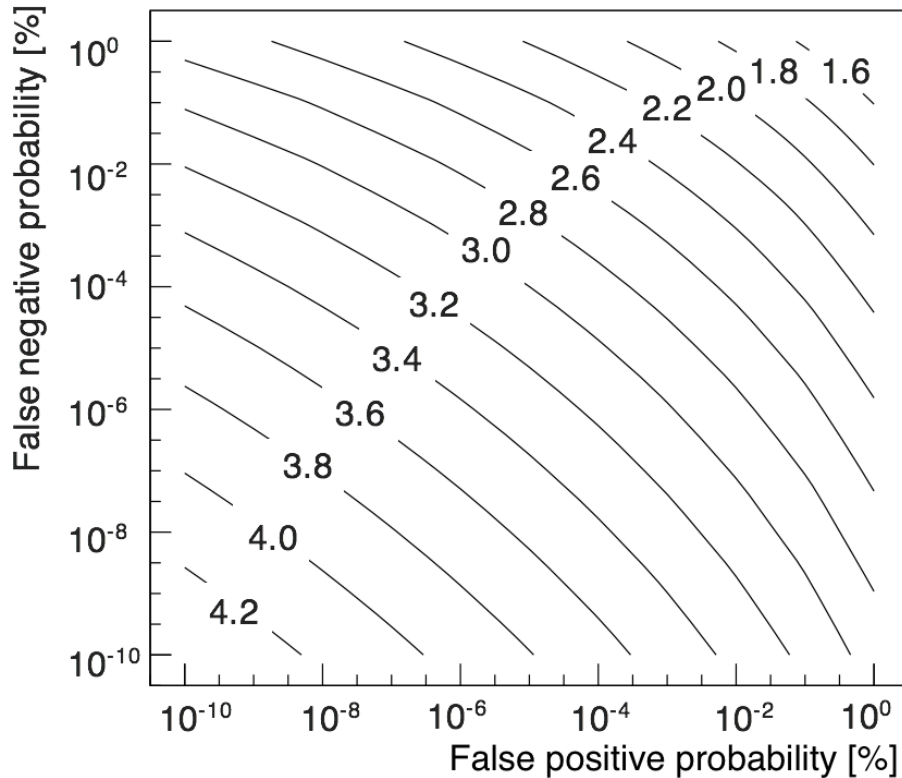
$^6\text{LiF}:\text{ZnS}(\text{Ag})$ 500 μm thick



Cd foil 500 μm thick

Receiver-operator curves for detection of 5 kg of ^{235}U

ROC; dose in mrem



Conclusions

- Prompt and delayed neutrons are powerful indicators of the fission process
- Room return can be challenging to account for even when nominally monoenergetic Al probe sources are used
- Neutron transmission detectors at moderate distances may also measure sufficient signal to accurately determine the fissile material mass
- Time-dependent delayed neutron emission can be detected over long time scales with high accuracy and is in agreement with simulation —> potential for isotopic discrimination
- In all cases, more complex configurations must be investigated to assess the limitations of model predictions



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